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Measurement of B Decays to $\phi K \gamma$

The *BABAR* Collaboration

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Abstract

We measure the branching fraction of the radiative B^- decay $\mathcal{B}(B^- \to \phi K^- \gamma) = (3.46 \pm 0.57^{+0.39}_{-0.37}) \times 10^{-6}$, and set an upper limit on the radiative $\overline{B}^0$ decay $\mathcal{B}(\overline{B}^0 \to \phi \overline{K}^0 \gamma) < 2.71 \times 10^{-6}$ at 90% confidence level. We also measure the direct *CP* asymmetry of the $B^- \to \phi K^- \gamma$ mode $\mathcal{A}_{CP} = (-26.4 \pm 14.3 \pm 4.8)\%$. The uncertainties are statistical and systematic, respectively. These measurements are based on 207 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector.

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Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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The *BABAR* Collaboration,

B. Aubert, R. Barate, M. Bona, D. Boutigny, F. Couderc, Y. Karyotakis, J. P. Lees, V. Poireau, V. Tisserand, A. Zghiche

Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France

E. Grauges

Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain

A. Palano

Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy

J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu

Institute of High Energy Physics, Beijing 100039, China

G. Eigen, I. Ofte, B. Stugu

University of Bergen, Institute of Physics, N-5007 Bergen, Norway

G. S. Abrams, M. Battaglia, D. N. Brown, J. Button-Shafer, R. N. Cahn, E. Charles, M. S. Gill, Y. Groysman, R. G. Jacobsen, J. A. Kadyk, L. T. Kerth, Yu. G. Kolomensky, G. Kukartsev, G. Lynch, L. M. Mir, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Ronan, W. A. Wenzel

Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

P. del Amo Sanchez, M. Barrett, K. E. Ford, A. J. Hart, T. J. Harrison, C. M. Hawkes, S. E. Morgan, A. T. Watson

University of Birmingham, Birmingham, B15 2TT, United Kingdom

T. Held, H. Koch, B. Lewandowski, M. Pelizaeus, K. Peters, T. Schroeder, M. Steinke

Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

J. T. Boyd, J. P. Burke, W. N. Cottingham, D. Walker

University of Bristol, Bristol BS8 1TL, United Kingdom

D. J. Asgeirsson, T. Cuhadar-Donszelmann, B. G. Fulsom, C. Hearty, N. S. Knecht, T. S. Mattison, J. A. McKenna

University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

A. Khan, P. Kyberd, M. Saleem, D. J. Sherwood, L. Teodorescu

Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

V. E. Blinov, A. D. Bukin, V. P. Druzhinin, V. B. Golubev, A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, K. Yu Todyshev

Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

D. S. Best, M. Bondioli, M. Bruinsma, M. Chao, S. Curry, I. Eschrich, D. Kirkby, A. J. Lankford, P. Lund, M. Mandelkern, R. K. Mommsen, W. Roethel, D. P. Stoker

University of California at Irvine, Irvine, California 92697, USA

S. Abachi, C. Buchanan

University of California at Los Angeles, Los Angeles, California 90024, USA

S. D. Foulkes, J. W. Gary, O. Long, B. C. Shen, K. Wang, L. Zhang
University of California at Riverside, Riverside, California 92521, USA

H. K. Hadavand, E. J. Hill, H. P. Paar, S. Rahatlou, V. Sharma
University of California at San Diego, La Jolla, California 92093, USA

J. W. Berryhill, C. Campagnari, A. Cunha, B. Dahmes, T. M. Hong, D. Kovalskyi, J. D. Richman
University of California at Santa Barbara, Santa Barbara, California 93106, USA

T. W. Beck, A. M. Eisner, C. J. Flacco, C. A. Heusch, J. Kroseberg, W. S. Lockman, G. Nesom, T. Schalk, B. A. Schumm, A. Seiden, P. Spradlin, D. C. Williams, M. G. Wilson
University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

J. Albert, E. Chen, A. Dvoretskii, F. Fang, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter, A. Ryd, A. Samuel
California Institute of Technology, Pasadena, California 91125, USA

G. Mancinelli, B. T. Meadows, K. Mishra, M. D. Sokoloff
University of Cincinnati, Cincinnati, Ohio 45221, USA

F. Blanc, P. C. Bloom, S. Chen, W. T. Ford, J. F. Hirschauer, A. Kreisel, M. Nagel, U. Nauenberg, A. Olivas, W. O. Ruddick, J. G. Smith, K. A. Ulmer, S. R. Wagner, J. Zhang
University of Colorado, Boulder, Colorado 80309, USA

A. Chen, E. A. Eckhart, A. Soffer, W. H. Toki, R. J. Wilson, F. Winklmeier, Q. Zeng
Colorado State University, Fort Collins, Colorado 80523, USA

D. D. Altenburg, E. Feltresi, A. Hauke, H. Jasper, J. Merkel, A. Petzold, B. Spaan
Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany

T. Brandt, V. Klose, H. M. Lacker, W. F. Mader, R. Nogowski, J. Schubert, K. R. Schubert, R. Schwierz, J. E. Sundermann, A. Volk
Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

D. Bernard, G. R. Bonneaud, E. Latour, Ch. Thiebaux, M. Verderi
Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France

P. J. Clark, W. Gradl, F. Muheim, S. Playfer, A. I. Robertson, Y. Xie
University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

M. Andreotti, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Luppi, M. Negrini, A. Petrella, L. Piemontese, E. Prencipe
Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

F. Anulli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, S. Pacetti, P. Patteri, I. M. Peruzzi,[1] M. Piccolo, M. Rama, A. Zallo
Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

[1]Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

A. Buzzo, R. Capra, R. Contri, M. Lo Vetere, M. M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi

Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy

G. Brandenburg, K. S. Chaisanguanthum, M. Morii, J. Wu

Harvard University, Cambridge, Massachusetts 02138, USA

R. S. Dubitzky, J. Marks, S. Schenk, U. Uwer

Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

D. J. Bard, W. Bhimji, D. A. Bowerman, P. D. Dauncey, U. Egede, R. L. Flack, J. A. Nash, M. B. Nikolich, W. Panduro Vazquez

Imperial College London, London, SW7 2AZ, United Kingdom

P. K. Behera, X. Chai, M. J. Charles, U. Mallik, N. T. Meyer, V. Ziegler

University of Iowa, Iowa City, Iowa 52242, USA

J. Cochran, H. B. Crawley, L. Dong, V. Eyges, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin

Iowa State University, Ames, Iowa 50011-3160, USA

A. V. Gritsan

Johns Hopkins University, Baltimore, Maryland 21218, USA

A. G. Denig, M. Fritsch, G. Schott

Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany

N. Arnaud, M. Davier, G. Grosdidier, A. Höcker, F. Le Diberder, V. Lepeltier, A. M. Lutz, A. Oyanguren, S. Pruvot, S. Rodier, P. Roudeau, M. H. Schune, A. Stocchi, W. F. Wang, G. Wormser

Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B.P. 34, F-91898 ORSAY Cedex, France

C. H. Cheng, D. J. Lange, D. M. Wright

Lawrence Livermore National Laboratory, Livermore, California 94550, USA

C. A. Chavez, I. J. Forster, J. R. Fry, E. Gabathuler, R. Gamet, K. A. George, D. E. Hutchcroft, D. J. Payne, K. C. Schofield, C. Touramanis

University of Liverpool, Liverpool L69 7ZE, United Kingdom

A. J. Bevan, F. Di Lodovico, W. Menges, R. Sacco

Queen Mary, University of London, E1 4NS, United Kingdom

G. Cowan, H. U. Flaecher, D. A. Hopkins, P. S. Jackson, T. R. McMahon, S. Ricciardi, F. Salvatore, A. C. Wren

University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom

D. N. Brown, C. L. Davis

University of Louisville, Louisville, Kentucky 40292, USA

J. Allison, N. R. Barlow, R. J. Barlow, Y. M. Chia, C. L. Edgar, G. D. Lafferty, M. T. Naisbit, J. C. Williams, J. I. Yi

University of Manchester, Manchester M13 9PL, United Kingdom

C. Chen, W. D. Hulsbergen, A. Jawahery, C. K. Lae, D. A. Roberts, G. Simi, J. Tuggle

University of Maryland, College Park, Maryland 20742, USA

G. Blaylock, C. Dallapiccola, S. S. Hertzbach, X. Li, T. B. Moore, S. Saremi, H. Staengle

University of Massachusetts, Amherst, Massachusetts 01003, USA

R. Cowan, G. Sciolla, S. J. Sekula, M. Spitznagel, F. Taylor, R. K. Yamamoto

Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA

H. Kim, S. E. Mclachlin, P. M. Patel, S. H. Robertson

McGill University, Montréal, Québec, Canada H3A 2T8

A. Lazzaro, V. Lombardo, F. Palombo

Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy

J. M. Bauer, L. Cremaldi, V. Eschenburg, R. Godang, R. Kroeger, D. A. Sanders, D. J. Summers, H. W. Zhao

University of Mississippi, University, Mississippi 38677, USA

S. Brunet, D. Côté, M. Simard, P. Taras, F. B. Viaud

Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7

H. Nicholson

Mount Holyoke College, South Hadley, Massachusetts 01075, USA

N. Cavallo,[2] G. De Nardo, F. Fabozzi,[3] C. Gatto, L. Lista, D. Monorchio, P. Paolucci, D. Piccolo, C. Sciacca

Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy

M. A. Baak, G. Raven, H. L. Snoek

NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands

C. P. Jessop, J. M. LoSecco

University of Notre Dame, Notre Dame, Indiana 46556, USA

T. Allmendinger, G. Benelli, L. A. Corwin, K. K. Gan, K. Honscheid, D. Hufnagel, P. D. Jackson, H. Kagan, R. Kass, A. M. Rahimi, J. J. Regensburger, R. Ter-Antonyan, Q. K. Wong

Ohio State University, Columbus, Ohio 43210, USA

N. L. Blount, J. Brau, R. Frey, O. Igonkina, J. A. Kolb, M. Lu, R. Rahmat, N. B. Sinev, D. Strom, J. Strube, E. Torrence

University of Oregon, Eugene, Oregon 97403, USA

[2]Also with Università della Basilicata, Potenza, Italy

[3]Also with Università della Basilicata, Potenza, Italy

A. Gaz, M. Margoni, M. Morandin, A. Pompili, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, C. Voci
Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy

M. Benayoun, H. Briand, J. Chauveau, P. David, L. Del Buono, Ch. de la Vaissière, O. Hamon, B. L. Hartfiel, M. J. J. John, Ph. Leruste, J. Malclès, J. Ocariz, L. Roos, G. Therin
Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France

L. Gladney, J. Panetta
University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

M. Biasini, R. Covarelli
Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy

C. Angelini, G. Batignani, S. Bettarini, F. Bucci, G. Calderini, M. Carpinelli, R. Cenci, F. Forti, M. A. Giorgi, A. Lusiani, G. Marchiori, M. A. Mazur, M. Morganti, N. Neri, E. Paoloni, G. Rizzo, J. J. Walsh
Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy

M. Haire, D. Judd, D. E. Wagoner
Prairie View A&M University, Prairie View, Texas 77446, USA

J. Biesiada, N. Danielson, P. Elmer, Y. P. Lau, C. Lu, J. Olsen, A. J. S. Smith, A. V. Telnov
Princeton University, Princeton, New Jersey 08544, USA

F. Bellini, G. Cavoto, A. D'Orazio, D. del Re, E. Di Marco, R. Faccini, F. Ferrarotto, F. Ferroni, M. Gaspero, L. Li Gioi, M. A. Mazzoni, S. Morganti, G. Piredda, F. Polci, F. Safai Tehrani, C. Voena
Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

M. Ebert, H. Schröder, R. Waldi
Universität Rostock, D-18051 Rostock, Germany

T. Adye, N. De Groot, B. Franek, E. O. Olaiya, F. F. Wilson
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

R. Aleksan, S. Emery, A. Gaidot, S. F. Ganzhur, G. Hamel de Monchenault, W. Kozanecki, M. Legendre, G. Vasseur, Ch. Yèche, M. Zito
DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France

X. R. Chen, H. Liu, W. Park, M. V. Purohit, J. R. Wilson
University of South Carolina, Columbia, South Carolina 29208, USA

M. T. Allen, D. Aston, R. Bartoldus, P. Bechtle, N. Berger, R. Claus, J. P. Coleman, M. R. Convery, M. Cristinziani, J. C. Dingfelder, J. Dorfan, G. P. Dubois-Felsmann, D. Dujmic, W. Dunwoodie, R. C. Field, T. Glanzman, S. J. Gowdy, M. T. Graham, P. Grenier,[4] V. Halyo, C. Hast, T. Hryn'ova, W. R. Innes, M. H. Kelsey, P. Kim, D. W. G. S. Leith, S. Li, S. Luitz, V. Luth, H. L. Lynch, D. B. MacFarlane, H. Marsiske, R. Messner, D. R. Muller, C. P. O'Grady, V. E. Ozcan, A. Perazzo, M. Perl, T. Pulliam, B. N. Ratcliff, A. Roodman, A. A. Salnikov, R. H. Schindler, J. Schwiening, A. Snyder, J. Stelzer, D. Su, M. K. Sullivan, K. Suzuki, S. K. Swain, J. M. Thompson, J. Va'vra, N. van

[4]Also at Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France

Bakel, M. Weaver, A. J. R. Weinstein, W. J. Wisniewski, M. Wittgen, D. H. Wright, A. K. Yarritu, K. Yi, C. C. Young

Stanford Linear Accelerator Center, Stanford, California 94309, USA

P. R. Burchat, A. J. Edwards, S. A. Majewski, B. A. Petersen, C. Roat, L. Wilden

Stanford University, Stanford, California 94305-4060, USA

S. Ahmed, M. S. Alam, R. Bula, J. A. Ernst, V. Jain, B. Pan, M. A. Saeed, F. R. Wappler, S. B. Zain

State University of New York, Albany, New York 12222, USA

W. Bugg, M. Krishnamurthy, S. M. Spanier

University of Tennessee, Knoxville, Tennessee 37996, USA

R. Eckmann, J. L. Ritchie, A. Satpathy, C. J. Schilling, R. F. Schwitters

University of Texas at Austin, Austin, Texas 78712, USA

J. M. Izen, X. C. Lou, S. Ye

University of Texas at Dallas, Richardson, Texas 75083, USA

F. Bianchi, F. Gallo, D. Gamba

Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy

M. Bomben, L. Bosisio, C. Cartaro, F. Cossutti, G. Della Ricca, S. Dittongo, L. Lanceri, L. Vitale

Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy

V. Azzolini, N. Lopez-March, F. Martinez-Vidal

IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain

Sw. Banerjee, B. Bhuyan, C. M. Brown, D. Fortin, K. Hamano, R. Kowalewski, I. M. Nugent, J. M. Roney, R. J. Sobie

University of Victoria, Victoria, British Columbia, Canada V8W 3P6

J. J. Back, P. F. Harrison, T. E. Latham, G. B. Mohanty, M. Pappagallo

Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

H. R. Band, X. Chen, B. Cheng, S. Dasu, M. Datta, K. T. Flood, J. J. Hollar, P. E. Kutter, B. Mellado, A. Mihalyi, Y. Pan, M. Pierini, R. Prepost, S. L. Wu, Z. Yu

University of Wisconsin, Madison, Wisconsin 53706, USA

H. Neal

Yale University, New Haven, Connecticut 06511, USA

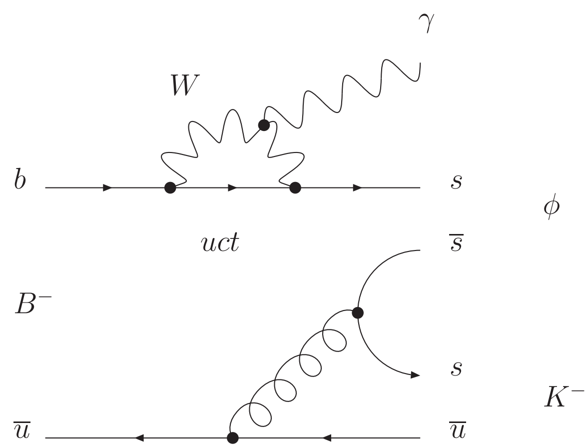

Figure 1: A leading order penguin diagram for $B^- \to \phi K^- \gamma$.

Measurements of the branching fractions and *CP* asymmetries of $b \to s\gamma$ decays provide a sensitive probe of the Standard Model (SM). In the SM these decays are forbidden at tree level but allowed through electroweak penguin processes (Fig. 1). They are therefore sensitive to the possible effects of new physics [1] in the form of new heavy particles contributing to the loop diagram. Additional contributions to the decay amplitudes could affect branching fractions and *CP* violation. Furthermore, the radiated photon is polarized due to the left-handed nature of the weak interaction. The polarization can be probed by measuring the time-dependent *CP* asymmetry, which is sensitive to interference between B^0-$\overline{B}^0$ mixing and decay. Theoretical estimates in the SM [2] bound the mixing-induced *CP* asymmetry at about the 10% level. Here we focus on the time-integrated direct *CP* asymmetry, which is expected to be the same for charged and neutral B decays.

Although exclusive $b \to s\gamma$ decays present a theoretical challenge due to large non-perturbative QCD interactions, they are experimentally clean. There have already been results published for branching fraction and/or *CP* asymmetry measurements in several exclusive modes: $B \to K^*\gamma$ [3], $B^0 \to K^0_S\pi^0\gamma$ [4], $B \to \eta(')K\gamma$ [5], and various $B \to K\pi\pi\gamma$ [6] modes. Here, we present a measurement of the branching fraction for the charged mode $B^- \to \phi K^- \gamma$ and the neutral mode $\overline{B}^0 \to \phi \overline{K}^0 \gamma$. [1] We also measure the direct *CP* asymmetry in the charged mode $\mathcal{A}_{CP} = [N(B^-) - N(B^+)]/[N(B^-)+N(B^+)]$, where the flavor of the B is determined by the charge of the kaon. The Belle Collaboration has previously measured the branching fractions for these modes, using $90\,\text{fb}^{-1}$ of $B\overline{B}$ data at the $\Upsilon(4S)$ resonance [7]. We describe the first *BABAR* measurements of these modes using a dataset that is more than twice as large.

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- storage ring. This analysis is based on a data set of $207\,\text{fb}^{-1}$ corresponding to 228 million $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance. The *BABAR* detector is described in detail elsewhere [8]. Important to this analysis are the tracking system composed of the silicon vertex tracker (SVT) and drift chamber (DCH), the detector of internally reflected Cherenkov light (DIRC), and the electromagnetic calorimeter (EMC). The SVT and DCH provide tracking and ionization energy loss ($\mathrm{d}E/\mathrm{d}x$) measurements for charged particles inside a 1.5 T magnetic field. The SVT is composed of five layers of double sided silicon strips and covers a polar angle range between 20.1^o and 150.2^o.

[1] Throughout this paper, whenever a mode is given, the charge conjugate is also implied.

The DCH continues tracking outside the SVT volume. It consists of 40 layers of hexagonal cells filled with an 80:20 mixture of helium:isobutane. The DIRC is a ring imaging Cherenkov light detector. Below 700 MeV/c the tracking system provides most of the charged particle identification (PID) information, while the DIRC contributes more information at higher momenta. Photons are detected and their energy measured in the EMC, which is composed of 6580 thallium-doped CsI crystals.

We select events with EMC clusters of energy $1.5 - 2.6$ GeV in the e^+e^- rest frame (CM frame) that are not associated with any charged track. Photon candidates are required to have an energy distribution consistent with the shower shape of an electromagnetic interaction, and they are required to be well isolated ($>$ 25 cm) from other calorimeter clusters. A veto is applied to photon candidates that can be combined with other neutral EMC clusters above a minimum threshold energy to form an invariant mass consistent with a π^0 ($115-155$ MeV/c^2) or η ($470-620$ MeV/c^2). The threshold energy is 50 MeV for π^0 and 250 MeV for η.

We select ϕ candidates from pairs of oppositely charged kaon tracks, determined not to be pions based on a PID likelihood selection algorithm that uses dE/dx and Cherenkov light measurements. The same algorithm is used for the single K^+ in the charged mode. The tracks are fitted to a vertex using a Kalman decay chain fitter [9], and are required to have a χ^2 vertex probability greater than 0.1%. We select candidates with masses within a 10 MeV/c^2 window of the nominal ϕ mass [10]. In the neutral mode, pairs of oppositely charged tracks are fitted to a common decay vertex and accepted as K^0_S candidates if the fit yields a probability greater tha 0.1%. The invariant mass of the pair is required to be within 10 MeV/c^2 of the K^0_S mass. The flight length of is required to be greater than three times the uncertainty of that length. We require the combined ϕK invariant mass to be less than 3.0 GeV/c^2. In the neutral mode a D^0 veto is applied by removing candidates with a ϕK invariant mass within 10 MeV/c^2 of the D^0 mass.

The K, ϕ, and γ candidates are fitted to a common vertex and accepted as B candidates if the vertex probability is greater than 0.1%. To discriminate $B\overline{B}$ events against continuum background the ratio of Legendre moments L_2/L_0 is required to be less than 0.55. The L_i are defined by $L_i = \sum_j |p^*_j||\cos\theta^*_j|^i$, where the p^*_j are the CM momenta of all particles not used in reconstructing the signal B candidate, and the angle θ^*_j is between the particle's momentum and the thrust axis of the signal B. We require the cosine of the angle between the B candidate and the beamline, $\cos\theta^*_B$, to be in the range [-0.9,0.9] in the CM frame. We use two uncorrelated kinematic variables of the B candidate: the reconstructed mass $m_{\rm rec}$ and the missing mass $m_{\rm miss}$. The reconstructed mass is the B candidate invariant mass calculated from the reconstructed energy and momentum. This is required to be within $4.98 - 5.48$ GeV/c^2. The missing mass squared is $m^2_{\rm miss} = \left(p_{\rm Beams} - p_B^{\rm mass\ const.}\right)^2$, where $p_{\rm Beams}$ is the four-momentum of the beams and $p_B^{\rm mass\ const.}$ is the four-momentum of the $B \to \phi K\gamma$ candidate after a mass constraint on the B is applied. We require the missing mass to be in the range $5.12 - 5.32$ GeV/c^2.

To study event selection criteria we use simulated Monte Carlo (MC) events of signal, generic B decays, and $e^+e^- \to q\overline{q}$ continuum background, where $q = \{u, d, s, c\}$. Events are generated using `EVTGEN` [11] and the detector response simulated with `GEANT4` [12]. Signal Monte Carlo is generated according to the inclusive $b \to s\gamma$ scheme presented in reference [13], using $m_b = 4.62$ GeV/c^2 for the effective b quark mass. Exclusive signal MC is derived from this by using only the part of the hadronic mass spectrum above the ϕK threshold of 1.52 GeV/c^2. Our selection criteria were chosen to optimize the figure of merit $N_S/\sqrt{N_S + N_B}$ in the signal region, where N_S and N_B are the number of signal and background events, respectively, and the signal region is defined by $5.05 < m_{\rm Rec} < 5.4\,{\rm GeV}/c^2$, $5.27 < m_{\rm miss} < 5.29\,{\rm GeV}/c^2$, $|\cos\theta^*_B| < 0.8$, and $L_2/L_0 < 0.48$.

After all selection criteria are applied the average candidate multiplicity in events with at least one candidate is approximately 1.01 and 1.07 in the neutral and charged modes respectively. If multiple B candidates are found in an event, we select the best one based on a χ^2 formed from the value and uncertainty of the mass of the ϕ candidate and, in the neutral mode, the K_S^0 candidate. The remaining background comes from continuum combinatorics and from other B decay modes, which will be discussed later.

We use an extended maximum likelihood fit in four observables – $m_{\rm miss}$, $m_{\rm rec}$, L_2/L_0, and $\cos\theta_B^*$ – to extract the signal and combinatoric background yields. The likelihood $\mathcal{L}$ is defined in the following way:

$$\mathcal{L} = \frac{e^{-(N_S+N_B)}}{N!}\Pi_i^N\left[(N_S\mathcal{P}_S^i + N_B\mathcal{P}_B^i)\right]. \tag{1}$$

N_S and N_B are the fitted number of signal and background events. N is the total number of events used in the fit. $\mathcal{P}_S^i$ and $\mathcal{P}_B^i$ are products of the signal and background probability density functions (PDFs) for each event i. In the charged mode, in order to fit the *CP* asymmetries of the signal and the background, the numbers of B^+ and B^- events are determined separately: $N_j = \frac{1}{2}(1+f\mathcal{A}_{CP})n_j$, where $j = S$ or B; f is the flavor, defined as $+1$ for B^- and -1 for B^+; n_j and $\mathcal{A}_{CP}^j$ are the total yield and *CP* asymmetry of species j. In the neutral mode $N_j = n_j$.

The signal PDFs for $m_{\rm miss}$ and $m_{\rm rec}$ are parametrized as asymmetric, variable-width Gaussian functions:

$$f(x) = exp\left[\frac{-x^2}{2\sigma_{L,R}^2 + \alpha_{L,R}x^2}\right]. \tag{2}$$

The parameters $\sigma_{L,R}$ and $\alpha_{L,R}$ determine the core width and variation of the width on either side of $x = 0$. The $m_{\rm miss}$ background PDF is an ARGUS function [14], with the endpoint calculated on an event-by-event basis from the beam energy. The $m_{\rm rec}$ background PDF is modelled as a 2$^{\rm nd}$ degree polynomial. The L_2/L_0 distribution is modelled using a binned PDF with eight bins, because there is no *a priori* model for this distribution. There are seven parameters in the PDF due to the condition that the bins sum to unity. The signal and background models both use this form. The $\cos\theta_B^*$ distribution is modelled as a 2$^{\rm nd}$ degree polynomial in both signal and background; for true B candidates it is expected to follow $1-\cos^2\theta_B^*$.

We use a high statistics $B^0 \to K^{*0}(\to K^+\pi^-)\gamma$ control sample to determine our signal shape parameters. Once determined, these signal parameters are fixed for the fit to $B \to \phi K\gamma$ data, while all background shape parameters are allowed to vary. We fit for the number of signal and background events, and in the charged mode the signal and background *CP* asymmetry as well. The same fit is used with signal MC to determine the efficiency of the previously described selection criteria. Corrections to the efficiency are discussed below.

We apply several corrections to the fitted signal yield and efficiency before determining the branching fractions. Studies of simulated events show that our main sources of peaking backgrounds are nonresonant $B \to KK^+K^-\gamma$ events, and $B \to \phi K\pi^0$, $B \to \phi K\eta$, where the π^0 or η decay fakes a high energy photon. We estimate the amount of $B \to KK^+K^-\gamma$ contamination by fitting for the yield in ϕ mass sideband regions extending outside the signal region from 10 MeV/c^2 to 30 MeV/c^2 of the nominal ϕ mass. By interpolating into the signal region, we find and correct for 0.03 ± 1.5 and 5.4 ± 4.2 events for the neutral and charged modes respectively. These contributions are subtracted from the event yield found in the fit. We also subtract the expected amount of $B \to \phi K^*(\to K\pi^0)$ as determined by *BABAR* [16]: 0.27 neutral and 1.98 charged events. Because there have been no branching fraction measurements of $B \to \phi K\pi^0$, $B \to \phi K\eta$, we assume that the branching fraction of these modes is no more than three times that of $B \to \phi K^*$. Therefore, we assign an uncertainty

Channel	Yield	Efficiency	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{CP}$
$B^- \to \phi K^- \gamma$	$85.0 \pm 13.9^{+7.3}_{-6.9}$	$[21.9 \pm 1.6(\mathrm{syst})]\%$	$3.46 \pm 0.57^{+0.39}_{-0.37}$	$(-26.4 \pm 14.3 \pm 4.8)\%$
$\overline{B}^0 \to \phi \overline{K}^0 \gamma$	$8.0 \pm 5.5^{+1.8}_{-1.7}$ < 16.0	$[15.33 \pm 0.81(\mathrm{syst})]\%$	$1.35 \pm 0.92^{+0.31}_{-0.30}$ < 2.71	

Table 1: Summary of the branching fractions and direct *CP* asymmetry. In $\overline{B}^0 \to \phi \overline{K}^0 \gamma$ the 90% confidence level upper limit is also given.

of 0.51 neutral and 2.86 charged events due to nonresonant $B \to \phi K(\pi^0/\eta)$ background. To correct for any fit bias, we generate 1000 pseudo-experiments using our maximum likelihood PDFs with separate components for $B\overline{B}$ and continuum, and embedding signal events from the full simulation. The background components are generated using shape parameters determined from the full MC simulation. We correct for a bias of $+4.07 \pm 0.45$ events in the charged mode, due to correlations among the observables in signal MC events that are not accounted for in the fit. In the neutral mode we find a bias of -0.06 ± 0.20, and so we include 0.20 events in the systematic uncertainty of the yield. We correct for known efficiency differences between data and Monte Carlo in charged track, single photon, and K^0_S reconstruction. These corrections amount to 0.956 in the neutral mode and 0.975 in the charged mode. The corrected efficiencies are $(15.3 \pm 0.81)\%$ in the neutral mode and $(21.9 \pm 1.6)\%$ in the charged mode, where the uncertainties are systematic (discussed below).

The signal yields, efficiencies, branching fractions, and charged mode *CP* asymmetry are reported in Table 1. We calculate the central value of the branching fractions as:

$$BF = \frac{N_{\mathrm{sig}}}{N_{B\overline{B}} \cdot \varepsilon \cdot \mathcal{B}(\phi \to K^+K^-)[\frac{1}{2}\mathcal{B}(K^0_S \to \pi^+\pi^-)]}, \tag{3}$$

where N_{sig} is the corrected number of signal candidates, $N_{B\overline{B}} = (228.3 \pm 2.5) \times 10^6$ is the number of $B\overline{B}$ pairs recorded by *BABAR*, ε is the corrected efficiency, and the $(K^0_S \to \pi^+ \pi^-)$ term is only used in the neutral mode. The partial branching fractions are given by Ref. [10]. We measure $\mathcal{B}(\overline{B}^0 \to \phi \overline{K}^0 \gamma) = (1.35 \pm 0.92^{+0.31}_{-0.30}) \times 10^{-6}$ and $\mathcal{B}(B^- \to \phi K^- \gamma) = (3.46 \pm 0.57^{+0.39}_{-0.37}) \times 10^{-6}$. In the charged mode we measure $\mathcal{A}_{CP} = (-26.4 \pm 14.3 \pm 4.8)\%$. Fits to the missing mass and reconstructed mass distributions, projected into the signal region defined earlier, are shown in Figure 2. We use a set of 1000 pseudo-experiments in the neutral mode to determine the probability of obtaining a branching fraction less than or equal to our measured central value under the hypothesis that it is in fact the same as the charged mode. This was found to be 1.1%.

For the neutral mode we compute the 90% confidence level upper limit on the branching fraction. We use a Bayesian approach with an *a priori* probability for the branching ratio which is flat in the physical region $0 \leq \mathcal{B} \leq 1$, and zero elsewhere. The value of the likelihood function is computed by fixing the signal yield to a desired value and fitting the other free parameters on the data sample. The function is then integrated numerically. We account for systematic uncertainties on the yield by convolving the likelihood function with the distribution of the errors, before computing the upper limit. To determine the upper limit of the signal yield we use a Gaussian PDF having a width equal to the systematic uncertainty of the yield. Similarly for the efficiency uncertainty we use a Gaussian PDF having a width equal to the systematic error. After also applying the yield corrections discussed previously we obtain $\mathcal{B}(\overline{B}^0 \to \phi \overline{K}^0 \gamma) < 2.71 \times 10^{-6}$.

To determine the contribution from resonances decaying to ϕK we study the background-subtracted [15], efficiency corrected ϕK invariant mass distribution, shown in Figure 3. Using the

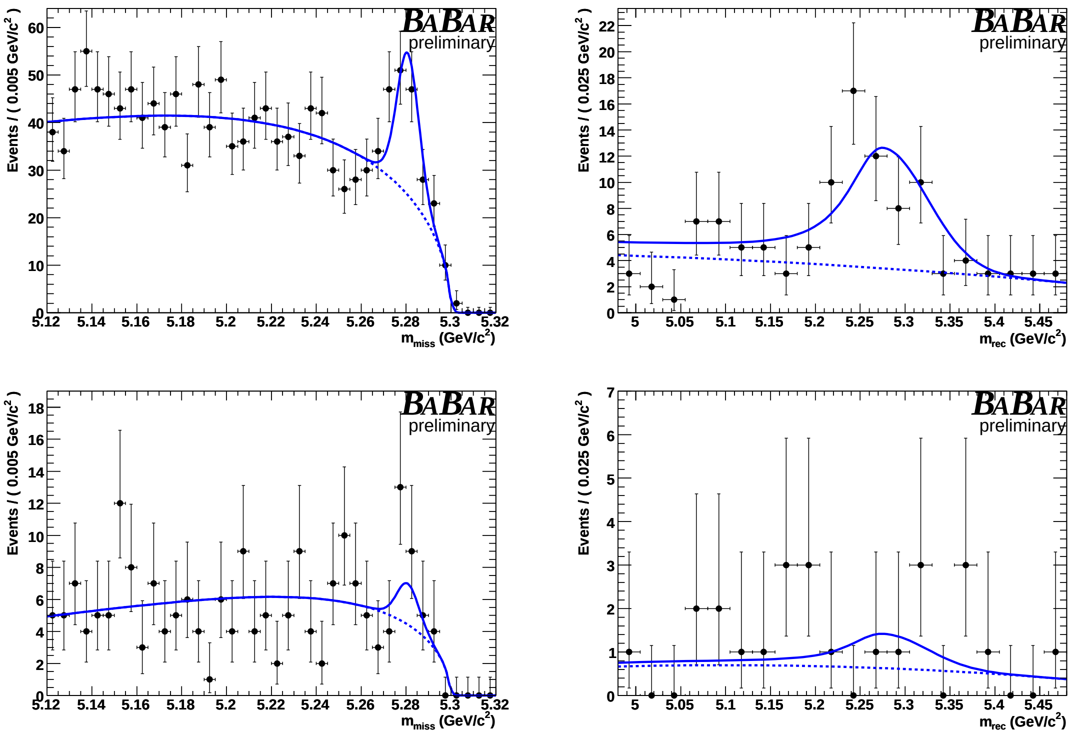

Figure 2: Missing mass (left) and reconstructed mass (right) fit projections in the signal region for the charged mode (upper) and the neutral mode (bottom). The dotted curves show the fitted background contribution while the solid curves show the signal.

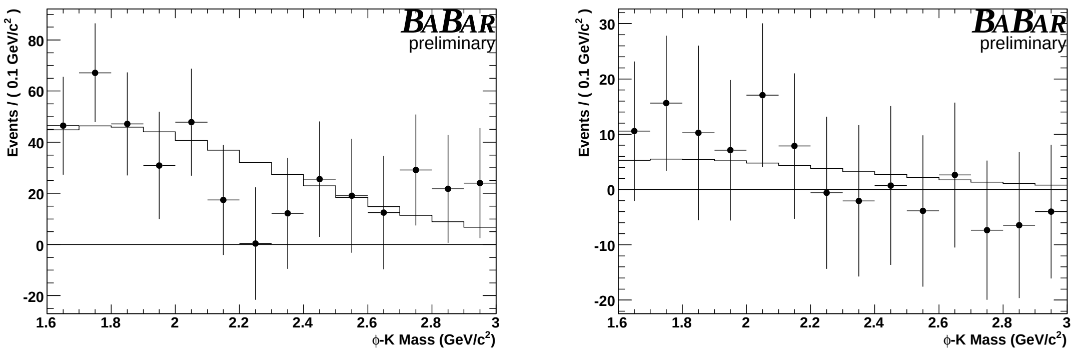

Figure 3: The background-subtracted and efficiency-corrected ϕK mass distributions (points with uncertainties) for the charged mode (left) and the neutral mode (right). The signal MC prediction for the mass spectrum, based on Ref. [13], is shown as a histogram without uncertainties.

charged mode, we find that no more than 50% of the spectrum in the $1.6-3.0$ GeV/c^2 range comes from the $K_2(1770)$ resonance. We use this to bound our model uncertainty, described below.

We assign an uncertainty due to the fixed signal parameters in the fit. The parameters were obtained from the control sample, and therefore they have some statistical uncertainty. We varied these parameters within their uncertainties to determine the total uncertainty on the yields. We account for other systematic uncertainties in charged kaon tracking, kaon PID, K_S^0, ϕ, and photon selection efficiency. There are small uncertainties assigned with our L_2/L_0 selection and the π^0/η veto. To account for uncertainty due to the assumption of a specific ϕK mass spectrum for simulated events, we determine what our efficiency would have been in the scenario that half of the spectrum comes from $K_2(1770)$ resonant ϕK production, while the other half comes from our signal MC model. We assign the relative efficiency difference as an uncertainty. Adding all of the uncertainties in quadrature, we find a total acceptance/efficiency uncertainty of 5.2% in the neutral mode and 7.1% in the charged mode. The contributions for each mode are summarized in Table 2.

For the direct *CP* asymmetry measurement we assume that the efficiency corrections and uncertainties cancel out. To account for uncertainty due to peaking background we use the following procedure. We assume an *a priori* flat distribution for the *CP* asymmetry between -1 and 1, which has a root mean square width of 0.58. We multiply this by the expected fractional contamination in our sample to obtain the systematic uncertainty. For $B^- \to \phi K^-(\pi^0/\eta)$ we assign 1.8% uncertainty, while for $B^- \to K^-K^+K^-\gamma$ we assign 3.5% uncertainty. For resonant $B \to \phi K^*(\to K\pi^0)$ events, the previous *BABAR* measurement [16] shows that the *CP* asymmetry is consistent with zero to within 9%. We therefore consider this to be negligible in our case. Using the control sample as we did with the branching fraction measurement, we vary the fixed input parameters of the fit to determine the uncertainty on the signal *CP* asymmetry. This was found to be 2.2%, bringing the total systematic uncertainty to 4.8%.

In summary, we have performed the first *BABAR* studies of $B \to \phi K\gamma$ decay modes. The $B^- \to \phi K^-\gamma$ branching fraction was measured, and an upper limit for the $\overline{B}^0 \to \phi\overline{K}^0\gamma$ mode was determined. Our measurements are consistent with the assumption of isospin symmetry at the 1.1% level. We have made the first measurement of the direct *CP* asymmetry in $B^- \to \phi K^-\gamma$. For comparison, we quote the Belle results [7]: $\mathcal{B}(B^- \to \phi K^-\gamma) = (3.4 \pm 0.9 \pm 0.4) \times 10^{-6}$ and

Source	$\overline{B}^0 \to \phi K^0_S\gamma$ Uncertainty	$B^- \to \phi K^-\gamma$ Uncertainty
$K\ K^+K^-\gamma$ subtraction	19.7%	5.2%
Peaking Background	6.4 %	3.4%
Fit Bias	2.6 %	0.6%
Fit PDF parameters	$^{+7.0}_{-5.9}$ %	$^{+5.9}_{-5.2}$ %
Total yield uncertainty	$^{+1.8}_{-1.7}$ events	$^{+7.3}_{-6.9}$ events
Kaon Tracking	2.8%	4.2%
K^0_S Efficiency	1.5%	0%
ϕ Efficiency	1.7%	1.7%
Particle ID	2.8%	4.2%
Single Photon Efficiency	1.8%	1.8%
Photon Spectrum Model	0.4%	2.6%
L_2/L_0 Cut	1.2%	1.2%
π^0/η Veto	1%	1%
Efficiency/acceptance uncertainty	**5.2%**	**7.1%**
$B\overline{B}$ **Counting**	**1.1%**	**1.1%**
Total	$^{+23}_{-22}$ %	$^{+11.2}_{-10.8}$%

Table 2: Summary of the systematic uncertainties.

$\mathcal{B}(\overline{B}^0 \to \phi \overline{K}^0\gamma) < 8.3 \times 10^{-6}$ at 90% confidence level. The statistical uncertainties will improve as the B Factories collect more data over the next several years. In future measurements a large amount of *CP* violation would be a sign of physics beyond the Standard Model.

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